Computational design and development of a new, lightweight cast alloy for advanced cylinder heads in high-efficiency, light-duty engines

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General Motors

6/20/2018

Project ID #mat061

Overview

Timeline

Project start date 02/2013

Project end date 06/2018

Percent complete 95%

Budget

- Total project funding
  - DOE share $3,498,650
  - Contractor share $1,646,423
- Funding **received** in FY17
  - $346,293
- Funding for FY18 planned
  - $559,365

Barriers

Engine Durability

- Current materials limit engine efficiency by limiting peak cylinder temperatures and pressures
- Insufficient tensile and fatigue properties beyond 150 C

Material Cost

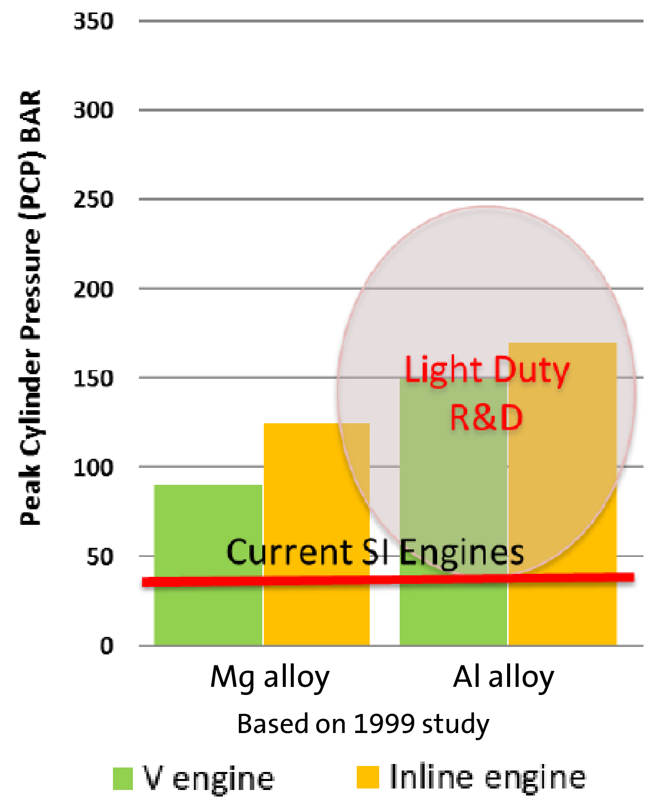
Partners

- Questek Innovations LLC
- Northwestern University
- American Foundry Society
- Dr. Fred Major
- Camaneo Associates
- **Project lead** General Motors

Relevance- Project Objectives

DOE FOA 648-3a Material Property Targets

Property	Baseline	DOE Target
Tensile Strength (ksi/MPa)	33/227	40/276
Yield Strength (ksi/MPa)	24/165	30/207
Elongation (%)	3.5	3.5
Shear Strength (ksi/MPa)	26/179	30/207
Endurance Limit (ksi/MPa)	8.5/59	11/76
Fluidity (Spiral test)	Excellent	Excellent
Hot Tearing Resistance	Excellent	Excellent
Tensile Strength (ksi/MPa)	7.5/52 @250 C	9.5/65 @300 C
Yield Strength (ksi/MPa)	5.0/34 @250 C	6.5/45 @300 C



To meet energy efficiency targets, peak engine pressures and temperatures will greatly exceed current material properties and therefore material needs to be improved

Relevance - Project Objectives 2017-2018

VTO Lightweight materials

Increase understanding of materials through modelling and computation

Material property improvement (strength, stiffness, and/or ductility)

GM lightweight cast alloy project

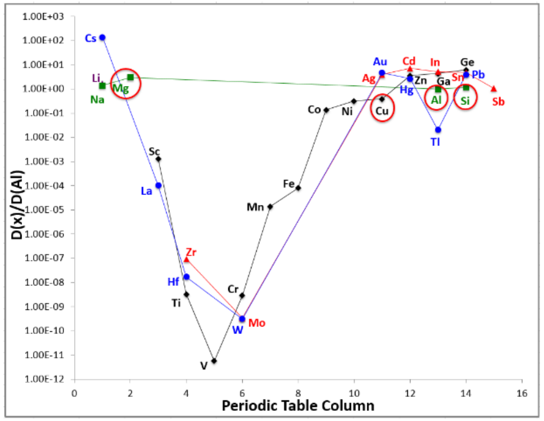
High resolution LEAP validation of slow diffusing elements predicted to segregate to the Q-phase

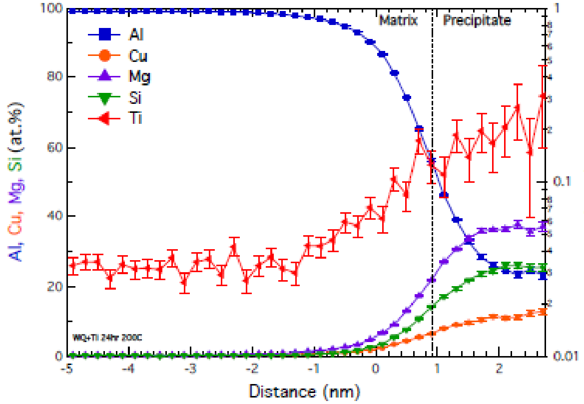
Material strength model predictions based on growth kinetics of Q-phase precipitates

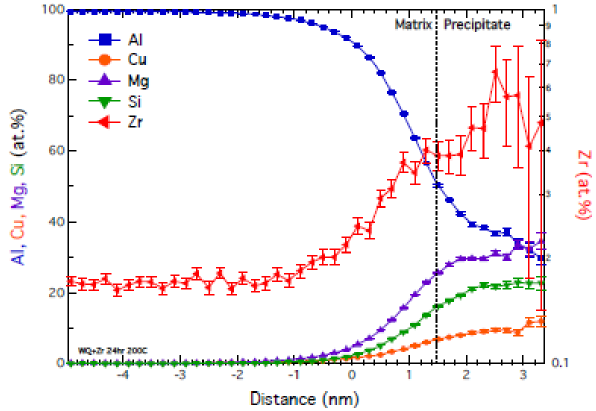
Tensile, fatigue, X-ray, and microstructural analysis of alloys cast into cylinder heads for validation of alloy in a semi-production environment.

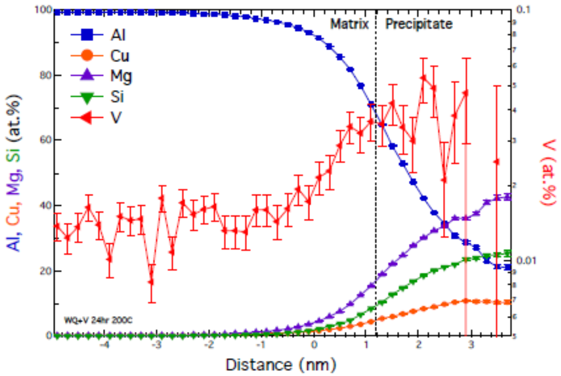
Approach/Strategy 2017/2018

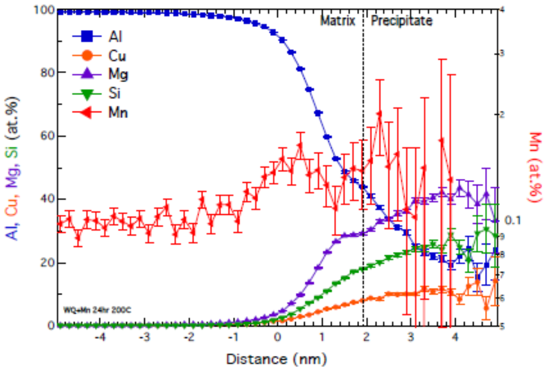
Stabilizing Q-phase with slow diffusing elements that segregate to the Q-phase











Approach/Strategy 2017/2018

Extensive testing of material properties on cylinder heads

	Test Temperature	ExDeck1	FDeck1	InDeck2	InDeck3	InDeck4	RDeck4	CC2	CC3	CC4	HPOL1	HPOL2	HPOL3	HPOL4	EBB2	EBB3	EBB4	Subtotal
Layout & cut up																		560
Tensile unconditioned	RT	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	26
Tensile unconditioned	150C	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	26
Tensile conditioned	200C	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	26
Tensile conditioned	250C	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	9
Tensile conditioned	300C	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	9
LCF unconditioned	RT	3	3	3	3	3	3	3	3	3	4	4	4	4	3	3	3	52
LCF unconditioned	150C	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	61
LCF conditioned	200C	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	61
LCF conditioned	250C	3	3	3	3	3	3	3	3	3	0	0	0	0	0	0	0	27
LCF conditioned	300C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HCF unconditioned	RT	3	3	3	3	3	3	3	3	3	5	5	5	5	4	4	4	59
HCF unconditioned	150C	3	3	3	3	3	3	3	3	3	5	5	5	5	4	4	4	59
HCF conditioned	200C	3	3	3	3	3	3	3	3	3	5	5	5	5	4	4	4	59
HCF conditioned	250C	3	3	3	3	3	3	3	3	3	0	0	0	0	0	0	0	27
HCF conditioned	300C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Micro		2	2	2	2	2	2	2	2	2	1	1	1	1	3	3	3	31
Spare		2	2	2	2	2	2	2	2	2	1	1	1	1	2	2	2	28
Totals		35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	560

Milestones 2017-2018

Milestone	Date planned / completed
11. Lab Scale Castings Completed	09/16 Planned New date 05/18
12. Component-scale Casting Completed	07/16 Planned Completed 04/18
13. Recyclability Analysis Completed	07/16 Planned New date 06/18
14. Properties of Final Alloy Validated	09/17 Planned New date 06/18
15. Final Cost Models Completed	09/17 Planned New date 06/18

Project has been extended to 06/18 because of the unfortunate closing of GM foundry due to renovations and asbestos removal. This has delayed lab scale casting production and subsequent milestones.

Technical Accomplishments

A comparison of mechanical properties from two Engine Trials

Deckface and Combustion Chamber

Property	DOE Target	Baseline Trial 1	Alloy 2 Trial 1	Baseline Trial 2	Alloy 3 Trial 2
UTS @ RT (MPa)	276	313	323	311	321
YS @ RT (MPa)	207	251	275	261	265
Elongation @ RT (%)	3.5	6.2	2.3	6.1	4.5
UTS @ 300 ^{o}C* (MPa)	65	41	56	42	52
YS @ 300 ^{o}C* (MPa)	45	38	49	40	45

* Samples conditioned at 300 ^{o}C for 100 hours

Technical Accomplishments

High cycle fatigue comparison of two trials

Deckface and Combustion Chamber

Temperature	Baseline Trial 1	Alloy 2 Trial 1	Baseline Trial 2	Alloy 3 Trial 2
25 ^{o}C	65.5 MPa	90.3 MPa	80.4 MPa	69.4 MPa
150 ^{o}C	63.6 MPa	76.2 MPa	78.5 MPa	56.5 MPa
250 ^{o}C	48.7 MPa	52.7 MPa	NA	47.1 MPa

High Pressure Oil Line

25 ^{o}C	71.2 MPa	70.5 MPa	43.5 MPa	60.2 MPa
150 ^{o}C	64.5 MPa	68.0 MPa	47.2 MPa	51.8 MPa

Bolt Boss

150 ^{o}C	64.2 MPa	85.0 MPa	65.0 MPa	70.0 MPa

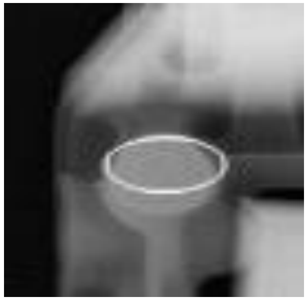
DOE Target 76 MPa at Room Temperature

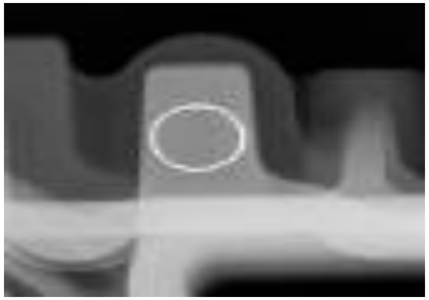
Samples above 150 ^{o}C conditioned for 100 hours at temperature

Technical Accomplishments

X-ray examination of castability in 2nd cylinder head casting trial

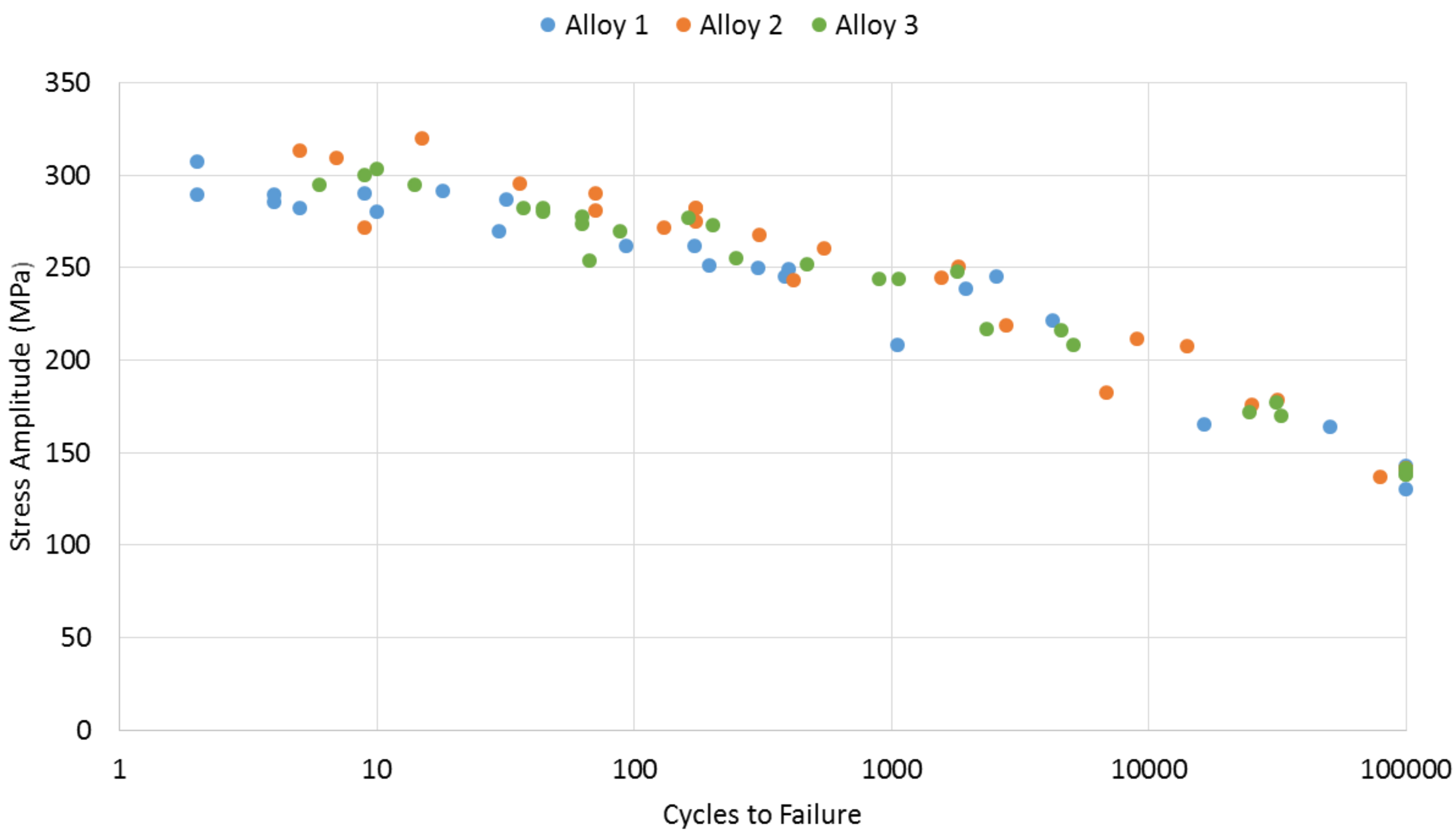
	Baseline Alloy 1	Alloy 3
Number of Castings	35	49
Number of defects per 100 castings	43	6
Number of defect castings per 100 castings	31	6





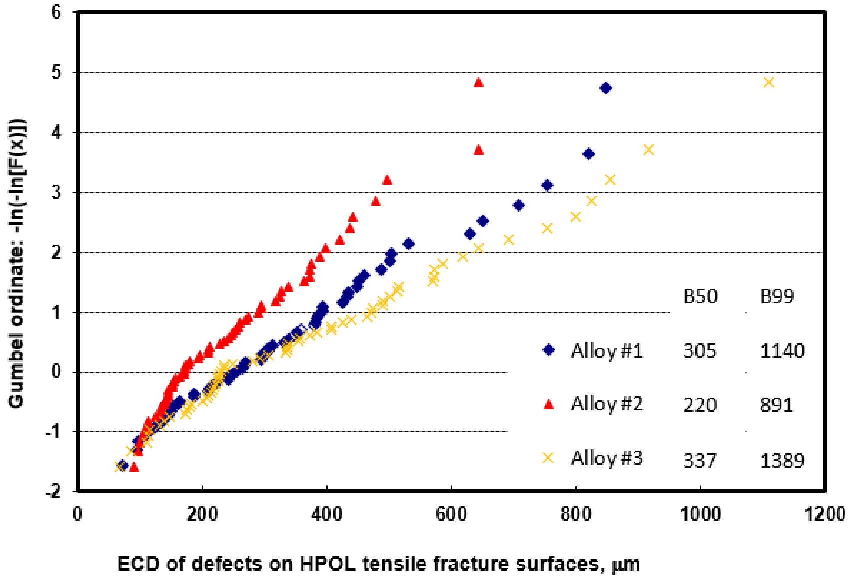
Technical Accomplishments

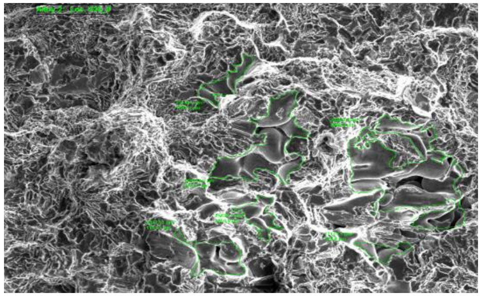
Low cycle fatigue comparison of combustion chamber and deckface regions at 150 ^{o}C

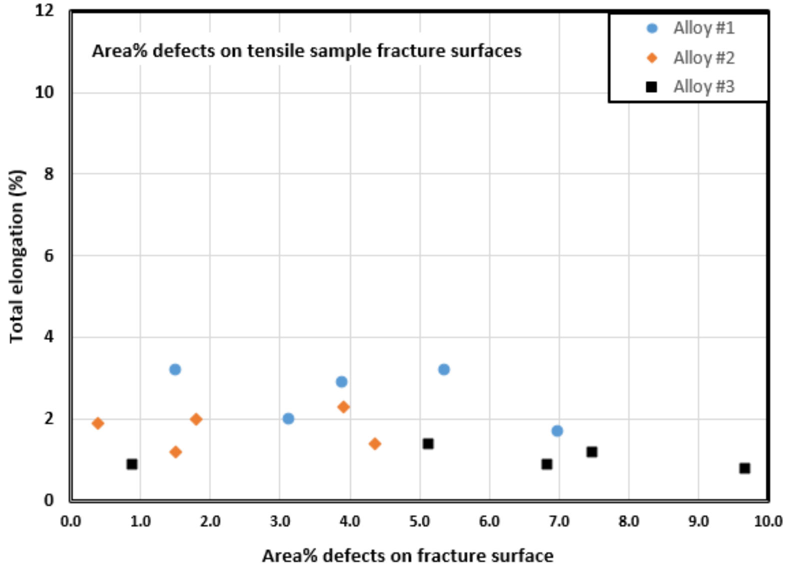


Technical Accomplishments

Microstructural evaluation of tensile fracture in slowly cooled areas

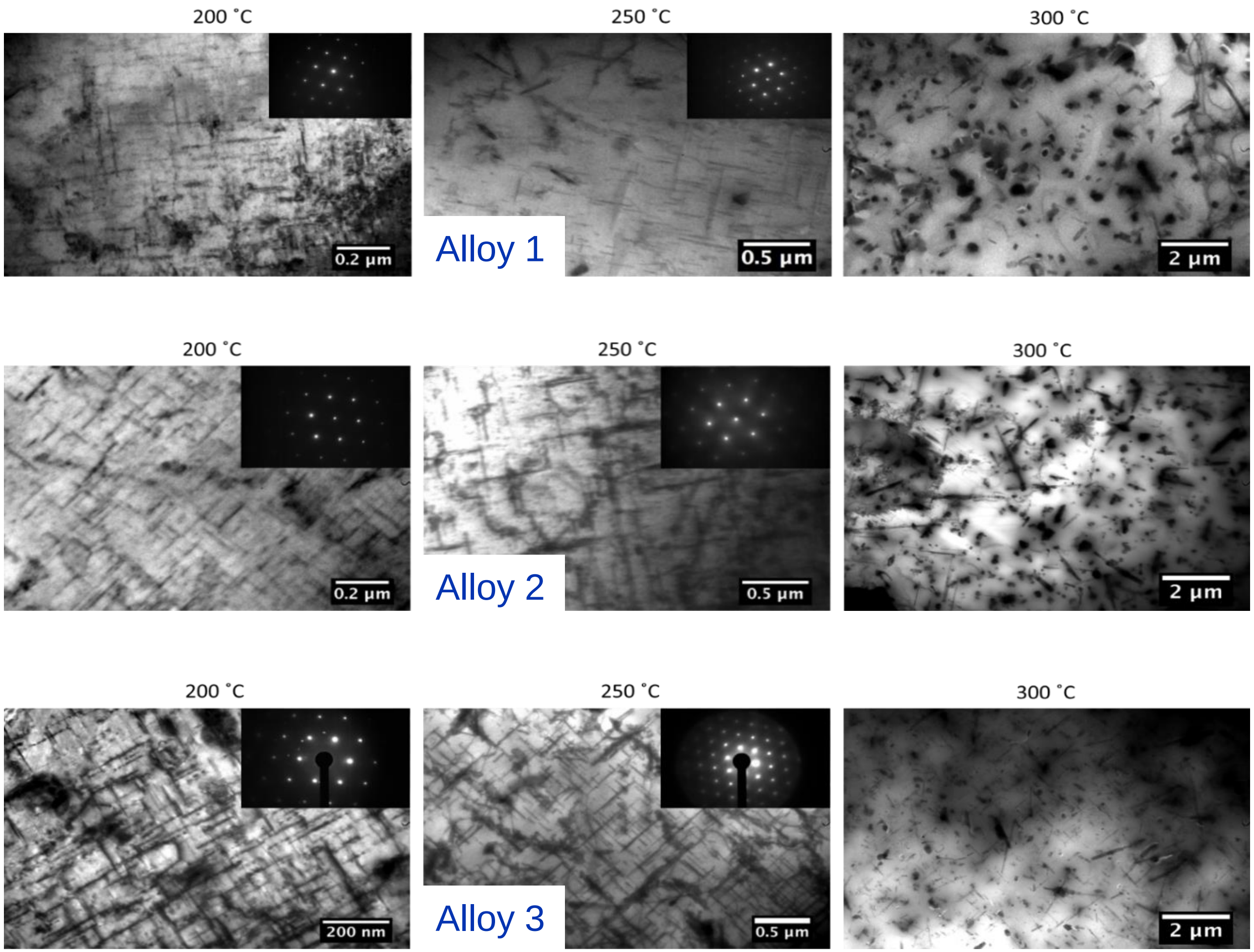






Head Casting Trial 1

Technical Accomplishments
TEM imaging of precipitate structure



TEM micrographs for three alloys. Images taken along <110>

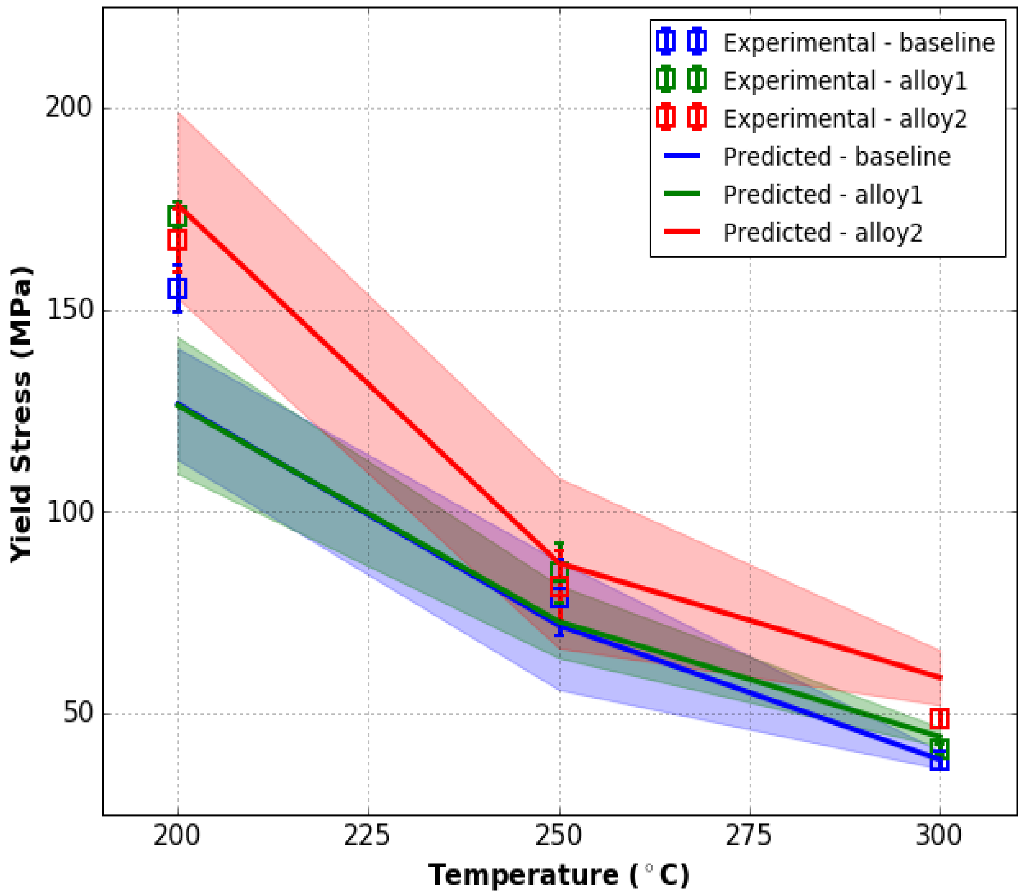
Technical Accomplishments

Precipitate length, radius, and coherency demonstrate the benefit at high temperature

Alloy	Baseline		Alloy 1		Alloy 2	
Temperature °C	Length nm	Radius nm	Length nm	Radius nm	Length nm	Radius nm
200	148 ± 50	5.4 ± 1.6	160 ± 38	6.2 ± 2.1	141 ± 51	3.7 ± 1.3
250	333 ± 130	15.8 ± 9.3	389 ± 147	16.0 ± 5.8	358 ± 129	13.3 ± 8.1
300		67 ± 23		55 ± 16		26 ± 11

Technical Accomplishments

Strength Model Prediction utilizing precipitate measurements



Collaboration and Coordination

General Motors – Principle Investigator

- Project administration, casting simulation, casting experiments, mechanical properties, microstructural evaluation, castability evaluation

QuesTek Innovations LLC – Industrial sub-partner

- Industrial Sub-partner
- ICME calculations – thermodynamics, kinetics, DFT alloy generation, alloy concept generation, parametric and final alloy designs, heat treatment process recommendations

Northwestern University – University sub-partner

- DFT alloy generation, Phase Field modelling of microstructure, experimental validation - Optical, SEM,TEM, LEAP

Fred Major, Zanya Connor(AFS),– Industrial sub-partners

- Technical advisors
- Recyclability analysis – SECAT Shridas Ningileri

Camanoe Associates – Industrial sub-partner - Process Based Cost Modelling

Future Work

2018

- Microstructural analysis of fatigue and tensile specimens from second head casting trial.
- Completion of mechanical testing
- Thermo-physical testing – thermo-conductivity and heat capacity
- Recyclability analysis
- Cost analysis of alloy and process

Summary

- Aluminum alloy strengthened with slow diffusing elements that segregate to the Q-phase.
- 2nd casting trial on engine cylinder heads to evaluate alloy in a semi-production environment.
- Measurements of room and high temperature tensile properties, HCF and LCF.
- Microstructural evaluation of fracture has identified porosity and intermetallic defect structures.
- X-ray evaluation of casting heads demonstrate excellent castability of the new alloys.